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14. ABSTRACT
The accuracy and relative merits of two sets of daily global sea surface temperature (SST) analyses are examined and compared. The 1/8° Modular Ocean Data Analysis System (MODAS) of the Naval Research Laboratory (NRL) is based only on infrared satellite retrievals. The 1/2° Real-Time, Global (RTG) SST analysis of the National Centers for Environmental Prediction (NCEP) supplements infrared satellite observations with ship and buoy data. The accuracy of both products is reported, providing potential users of either data set a common basis to assess the strengths and weaknesses of either product. Differences between the two show the impact of horizontal resolution, inclusion of source data streams, and different assumptions regarding error covariances. The global average of the root-mean-square (RMS) SST difference between MODAS and RTG is found to be 0.51°C, with almost no mean bias. A global set of yearlong daily SST time series from moored buoys during 2002-2005 provides extensive validation data for this study. Comparisons at the locations of these 420 yearlong time series give a median RMS SST difference of 0.40°C between MODAS and RTG. RMS error relative to the buoy observations is comparable, 0.38°C for MODAS and 0.36°C for RTG. The seasonal cycle of SST is well produced by both products with respect to the buoys with a median correlation coefficient of 0.94 for both products. Overall, higher resolution is an advantage for MODAS in improving pattern of daily SSTs, while including in situ SSTs is an advantage for RTG.

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Fine-resolution satellite-based daily sea surface temperatures over the global ocean

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[1] The accuracy and relative merits of two sets of daily global sea surface temperature (SST) analyses are examined and compared. The 1/8° Modular Ocean Data Analysis System (MODAS) of the Naval Research Laboratory (NRL) is based only on infrared satellite retrievals. The 1/2° Real-Time, Global (RTG) SST analysis of the National Centers for Environmental Prediction (NCEP) supplements infrared satellite observations with ship and buoy data. The accuracy of both products is reported, providing potential users of either data set a common basis to assess the strengths and weaknesses of either product. Differences between the two show the impact of horizontal resolution, inclusion of source data streams, and different assumptions regarding error covariances. The global average of the root-mean-square (RMS) SST difference between MODAS and RTG is found to be 0.51°C, with almost no mean bias. A global set of yearlong daily SST time series from moored buoys during 2002–2005 provides extensive validation data for this study. Comparisons at the locations of these 420 yearlong time series give a median RMS SST difference of 0.40°C between MODAS and RTG. RMS error relative to the buoy observations is comparable, 0.38°C for MODAS and 0.36°C for RTG. The seasonal cycle of SST is well produced by both products with respect to the buoys with a median correlation coefficient of 0.94 for both products. Overall, higher resolution is an advantage for MODAS in improving pattern of daily SSTs, while including in situ SSTs is an advantage for RTG.

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1. Introduction

[2] The availability of accurate daily sea surface temperature (SST) is essential for a variety of applications. Daily SST is a key remotely observable property that is used to identify ocean circulation features, and its accuracy is critical in monitoring the evolution of currents, fronts and eddies on short time scales [e.g., *Smedstad et al.*, 2003]. Reliable SSTs are necessary not only for short range weather forecasts [*Quan et al.*, 2004], but also monitoring climate changes [*Webster*, 1995] and El Niño Southern Oscillation (ENSO) events [*Diaz and Markgraf*, 2000] as well. The international Global Ocean Data Assimilation Experiment (GODAE), whose major focus is to produce forecasts of ocean currents and temperatures up to 30 days in advance over the ocean, has highlighted the need for an operational high temporal and spatial resolution SST product [*Smith*, 2000].

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[3] While numerical weather prediction (NWP) products provide high temporal resolution (e.g., 3 or 6 hourly) SSTs, their coarse spatial resolutions (e.g., 1° × 1°) hamper one's ability to resolve small to mesoscale features over the global ocean. Some commonly used NWP products include the 1.125° × 1.125° European Centre for Medium-Range Weather Forecasts (ECMWF) 40-year Re-Analysis (ERA-40) [*Kållberg et al.*, 2004], 1.875° × 1.875° NCEP re-analysis [*Kanamitsu et al.*, 2002], and 1° × 1° Fleet Numerical Meteorology and Oceanography Center (FNMOC) Navy Operational Global Atmospheric Prediction System (NOGAPS) [*Rosmond et al.*, 2002]. All these NWP products also rely on quality-controlled observational data sets for assimilation, revealing the need for a SST product which has fine spatial and temporal scales over the global ocean. Improvements and upgrades to the quality of these NWP products clearly deserve a better and increased use of quality SST products.

[4] As explained above, there is a high demand in having daily SSTs on fine spatial scales (e.g., <1/2°) over the global ocean. Ships and moored and drifting buoys provide SSTs with good temporal frequency and acceptable accuracy, but their spatial coverage is limited globally. Satellite retrievals

are one possible source for obtaining SSTs over the global ocean. Satellites provide information with global coverage in principle, good horizontal and temporal resolution and acceptable accuracies once they are calibrated using in situ data. Sea surface observations using the infrared and visible portions of the spectrum may be obscured by clouds. in particular, the infrared wavelengths used by the Advanced Very-High Resolution Radiometer (AVHRR) sensor are sensitive to the presence of clouds and scattering by aerosols and atmospheric water vapor. One challenge is to appropriately fill in regions where SST measurements are obscured, degraded or otherwise not available. Various approaches may be used to transform the irregularly sampled and cloud-obscured AVHRR SST data into a more regular product [e.g., *Casey and Cornillon*, 1999; *Reynolds and Smith*, 1994].

[5] In this paper, we examine two products that are mainly based on AVHRR satellite measurements: the MODAS SST analysis [*Barron and Kara*, 2006] and the RTG SST analysis [*Thiébaux et al.*, 2003]. These products both fill SSTs in cloud-covered regions and provide gridded SSTs over the global ocean on daily time scales. As an example, SST obtained from both products is shown in Figure 1 over the global ocean. Further details about the geographical extent and other features for each product are provided in section 2.

[6] Four main features differentiate global MODAS and RTG products. These are as follows. (1) While MODAS has a resolution of 1/8°, RTG has a coarser resolution of 1/2°. (2) RTG makes uses of both satellite and in situ SSTs in generating the final SST product. However, MODAS uses only satellite SSTs. (3) MODAS spans latitudes from 80°S to 80°N, but RTG includes all latitudes. (4) While MODAS does not have a special treatment for ice-covered regions, RTG includes SSTs derived from satellite-observed sea-ice coverage.

[7] These differences between MODAS and RTG are to lead us to ask "what is the relative importance of horizontal resolution in producing daily SSTs?", and "does the use of satellite data along with in situ data provide a great benefit in comparison to the use of satellite data only for obtaining daily SSTs over the global ocean?". Answers to such questions are focus of this paper. In particular, our major goal is to examine accuracy of these two products and determine their relative advantages and disadvantages.

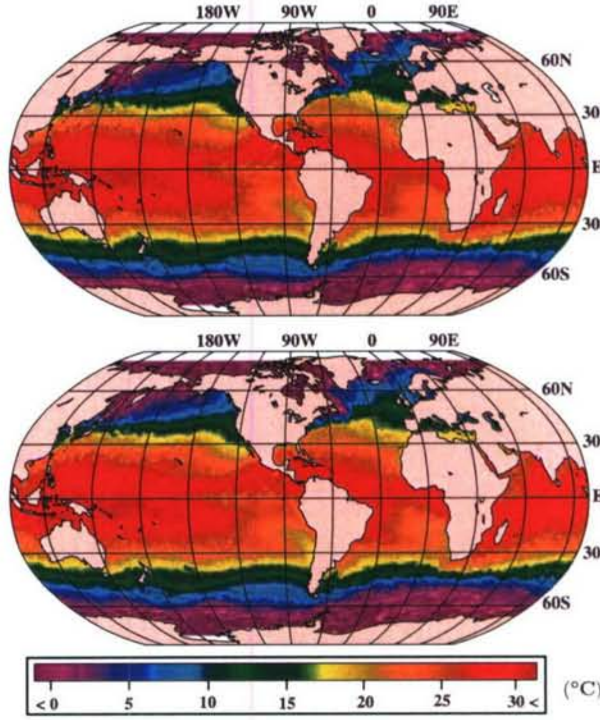

Figure 1. Spatial variation of SST over the global ocean on 1 Jan 2005, as obtained from MODAS (top) and RTG (bottom) products. While the former is based solely on the satellite measurement, the latter combines both satellite and in situ data to producing gridded SST. For plotting purposes, RTG has been interpolated to the same grid as MODAS with latitudinal extent limited to ±80°. Note that only the RTG product includes SST in the Caspian Sea and the Sea of Azov. The plot masks SST in the Great Lakes that may otherwise included in RTG.

2. Description of SST Products

[8] In this section we provide specific details about the two SST products (MODAS and RTG) used throughout the paper. While there are some fundamental differences in the way that they are produced, as described below, our main goal here is to discuss their major features, so that any user can get a general idea before using them for a particular purpose. Both products have a common feature, in that they produce daily global SST at relatively fine spatial scales.

2.1. MODAS SST

[9] MODAS SST is a purely satellite-based product [*Barron and Kara*, 2006]. It is produced on a uniform 1/8° (latitude, longitude) grid by an optimal interpolation (OI) of AVHRR nonlinear SST (NLSST) observations processed by the Naval Oceanographic Office (NAVOCEANO) [*May et al.*, 1998]. This subsurface or bulk SST represents conditions in the upper few meters measured by typical in situ instruments.

[10] All operational global AVHRR data from 1993 to the present have been used in the MODAS analysis, reflecting on any given day the collected data from one to three of the NOAA TIROS-N series of polar-orbiting satellites, from NOAA-11 to NOAA-18. While buoy data are used collectively to initially determine nonlinear SST coefficients [*Walton et al.*, 1998], none of the in situ SST data are individually assimilated into the MODAS SST gridded product. MODAS SST data older than 30 days are available on the the Live Access Server (LAS) at http://tampa.nrlssc.navy.mil:8000/las/servlets/dataset.

[11] MODAS analysis uses an OI approach to fill in data voids due to the presence of clouds. The approach is based on joint emphasis of accurate SST, fidelity in locating and quantifying SST gradients, and avoiding spurious gradients. The OI used in MODAS mitigates the artificial discontinuities associated with bin edges in composites or data voids in binned averages. It has three components: the

observations, the first guess or initial analysis, and the expected covariance of errors in the observations and first guess [*Lorenc*, 1981]. For MODAS, the first guess is derived using climatologically corrected persistence, where the MODAS SST analysis and expected errors for the prior day are smoothed and relaxed toward the MODAS bimonthly climatology [*Fox et al.*, 2002] with a 60-day time scale. Under episodic cloud cover, a lack of recent observations leads to a loss of confidence in the prior analysis and an increase in the expected error of the analysis. For extended cloudy periods, the first guess and its expected error tend toward climatological means and standard deviations.

[12] The OI is performed on the observation increments or innovation vector, defined as the SST observations minus the first guess SST. The MODAS analysis uses a Gaussian error covariance with 60-hour time and 20-km length scales. These scales were determined subjectively to balance fidelity in representing fronts with mitigation of spurious gradients around data-sparse regions. Longer length scales would produce a smoother product that avoids large artifical gradients in sparsely sampled regions but obscures details observed with dense sampling. Present work examining correlations of the observation increments will hopefully enable us to develop a spatially and perhaps temporally variable covariance model that reflects geographic differences and better accounts for correlated observations, which can be even more significant when using multiple satellite platforms.

[13] Finally, the OI results in the MODAS analysis increments or correction vector that reflects a balance between the representativeness and expected errors in the observations with uncertainty in the first guess field. Adding the correction vector to the first guess produces the SST analysis. In the present system, this analysis is relaxed toward climatology to derive the first guess for the next day.

2.2. RTG SST

[14] RTG SST has been developed at NCEP. It is based on a two dimensional variational interpolation analysis of the most recent 24-hours buoy and ship data, satellite-retrieved SST data, and SST's derived from satellite-observed sea-ice coverage [*Thiébaux et al.*, 2003]. It is generated once a day on a 1/2° (latitude × longitude) grid, and has been available since 11 Feb 2001. Specific details about the RTG SST analysis can also found online at http://polar.ncep.noaa.gov/sst/.

[15] The satellite SST retrievals used in the RTG analysis are the Navy's SEATEMP retrievals from NOAA-17 AVHRR data. They are averaged within 1/2° grid boxes with day and night super-obs created separately for each satellite. Bias calculation and removal for satellite retrieved SST are done as in *Reynolds and Smith* [1994]. SST reports from individual ships and buoys are separately averaged within grid boxes. The first-guess is the unsmoothed analysis with one-day's climate adjustment added. Late-arriving data which did not make it into the previous SST analysis are accepted if they are less than 36 hours old. RTG uses an inhomogeneous correlation scale parameter which is Gaussian with length scale of $\approx$100–450 km, much larger than what MODAS uses (20 km).

[16] The RTG SST analysis is performed over all ocean areas. Unlike MODAS, it also includes the Great Lakes in the United States. The land values in the RTG analysis are filled by the traditional Cressman interpolation [*Cressman*, 1959] to produce a complete grid for possible interpolation to other grids. As in the MODAS SST analysis, the ocean and land areas are defined by a land sea mask. As of this writing, there is also higher resolution (1/12°) version of the RTG SST analysis. It became fully operational on 27 Sep 2005 and has been generated using the similar data and analysis techniques as in the 1/2° RTG analysis. Our effort is an examination of MODAS and RTG over multiple years, longer time periods covered only by the 1/2° RTG product. Thus we do not examine the 1/12° product in this study.

3. SST Image Comparisons

[17] High-resolution satellite images are valuable for investigating the representation of circulation features and spatial variability. Thus, we have identified some particularly cloud-free images for comparison with snapshots of MODAS and RTG SST. Our characterization of the spatial fidelity is largely qualitative, focusing on whether frontal gradients or other features of interest evident in the high-resolution snapshot are similarly present in the gridded SST products.

[18] A good source for obtaining SST images is the the Aqua satellite launched by National Atmospheric Space Administration (NASA). One of the instruments carried aboard Aqua is the Moderate Resolution Imaging Spectroradiometer (MODIS), which measures radiance in the infrared bands. SST can be derived from the measurements in these bands. Radiances measured by the MODIS satellite instruments are emitted from within the surface skin layer of the ocean. MODIS/Aqua SST data have been calibrated primarily by the bulk SST of in situ and ship-board measurements [*Smith et al.*, 1996]. The calibration is necessary because the atmospheric corrections, to which the infrared measurement is sensitive, involve large uncertainties. MODIS SST can be regarded as a best representation of the bulk SST based on information from the space-borne instruments [*Donlon et al.*, 2002]. However, it should be kept in mind that MODIS algorithms for SST retrieval sometimes fail in the vicinity of fronts that have large SST gradients.

[19] Other satellite sources for SST images exist but due to their generally lower spatial resolution are less appropriate than the MODIS images for our purposes of characterizing spatial fidelity. Microwave-based instruments such as the Advanced Microwave Scanning Radiometer (AMSR) can measure SST under regions of cloud cover that obscure the infrared wavelengths of the MODIS and AVHRR windows. AMSR measurements are strongly dependent on surface roughness [e.g., *Dong et al.*, 2006], and, though not obscured by clouds, can be highly erroneous in areas of strong precipitation. While AMSR measures sub-skin SST, in practice it may be calibrated using in situ observations to have a mean representative of bulk SST [*Dong et al.*, 2006] and thus more compatible with the bulk-calibrated MODAS, RTG or MODIS SST.

[20] The biggest drawback to using AMSR SST images for identifying spatial detail is its resolution. MODIS swath

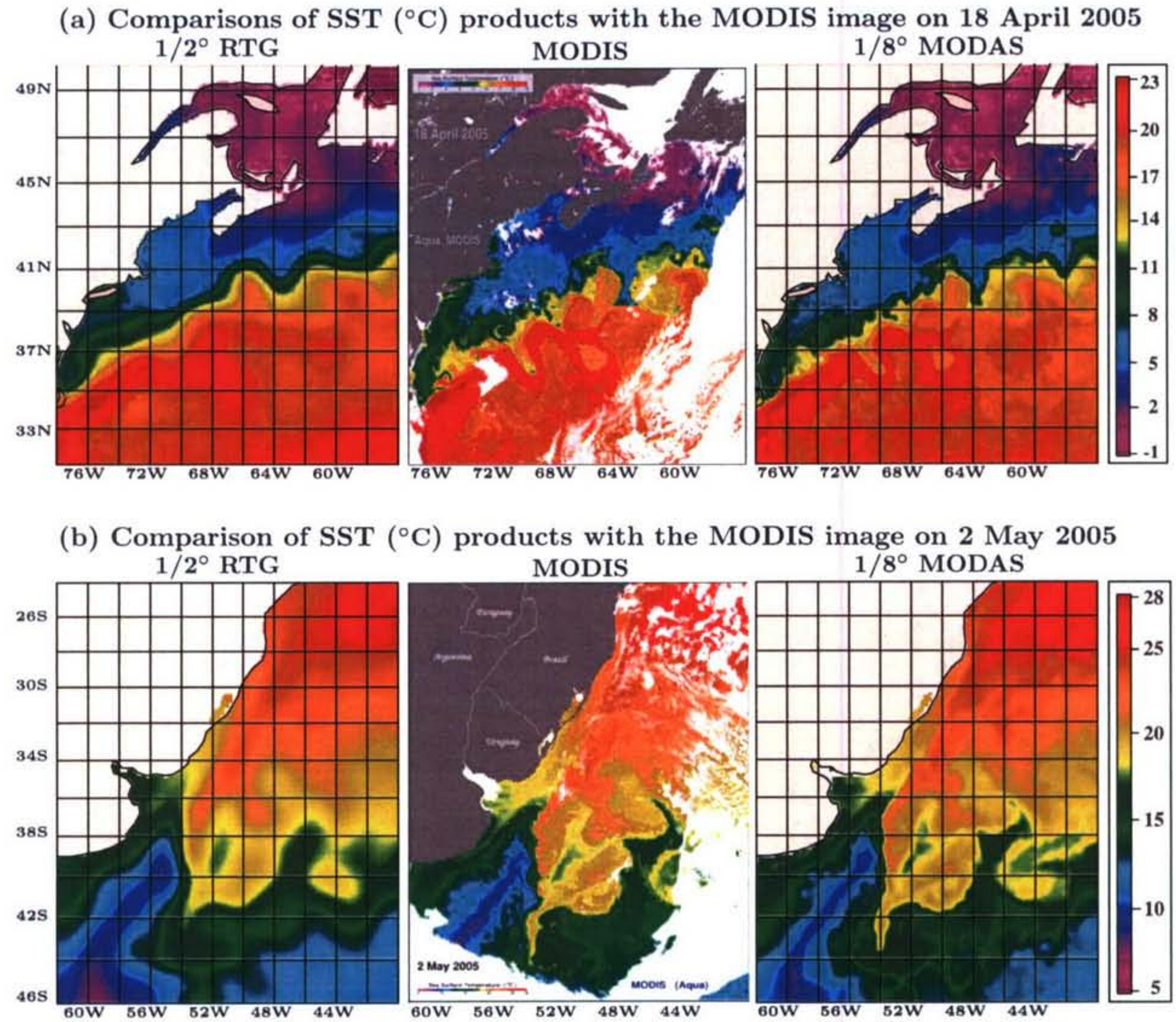

Figure 2. Comparison of spatial SST obtained from three different sources: MODIS (Aqua), MODAS and RTG. They are shown in two regions: (a) one including the Gulf Stream on 18 April 2005, and (b) one including the North Brazilian Current on 2 May 2005. MODIS swath resolution at nadir is $\approx$1 km($\approx$1/112°).

resolution at nadir is relatively fine ($\approx$1 km), in contrast with the coarse AMSR resolution, 50 to 75 km depending upon the microwave wavelength and about 0.25° in the multichannel processed data. AMSR SST is not reliable in coastal waters due to both the relatively large footprint and strong, misleading returns from land. Although SSTs from MODIS may be degraded or obscured by clouds, on the relatively cloud-free days selected for comparison they have good coverage and much higher spatial resolution compared to AMSR SSTs. For these reasons, we use MODIS SSTs for evaluations in this section.

[21] As a first example of image comparisons, spatial variations in SST as obtained from fine resolution ($\approx$1 km) MODIS (Aqua) are examined on 18 Apr 2005 (Figure 2a). The original image is available online at http://oceancolor.gsfc.nasa.gov. To facilitate comparison of images, we extracted the color bar from the MODIS SST image, determined the mapping from SST to color, and applied the same color map to the MODAS and RTG SST plots. The 1/2° resolution of the RTG is not sufficient to represent the spatial variation evident in the clear, full-resolution MODIS image. While the overall pathway is adequate, major Gulf Stream meanders are smeared out in RTG. The meander patterns in the MODAS SST are in closest agreement with the MODIS image, but MODAS at 1/8° is unable to capture the clear-sky detail of $\approx$1 km MODIS.

[22] A second clear-sky comparison using MODIS is available on 2 May 2005 (Figure 2b). Thus, we also examine differences in SST among MODIS, MODAS and RTG within this particular location. All of the SST products identify similar locations for a well-defined cold tongue extending northeast along the slope off Argentina to just

south of the Rio de la Plata, the large estuary between Argentina and Uruguay. Estimates of its temperature range from ≈5°C to ≈10°C, with RTG indicating the broadest plume and coldest temperatures. MODAS represents smaller-scale features relatively better than the coarse RTG. The locations of temperature patterns in MODAS result in the best agreement with the fine-scale MODIS. MODAS and RTG generally agree on the overall range and distribution of temperature over the broader region.

[23] Some of the differences between MODAS and RTG analyses are a result of different scales in the error covariances (see section 2). In general, RTG reflects large scale variability and tends to smooth out spatial features, producing a field that places a premium on avoiding large temperature errors. The shorter scales in MODAS attempt to resolve mesoscale features in the surface temperature, producing a better representation of gradients and features where data are abundant and likely producing larger temperature errors and spurious gradients where data are sparse (Figure 2). Longer time and length scales in RTG tend to make the field smoother in time and space, while shorter scales in MODAS will tend to draw closer to individual observations and reflect more variability. In an area of frequent observations and analysis, the shorter scales work well, but if data are sparse the shorter scales tend to produce bulls-eyes, accurate analyses near recent observations surrounded by spurious gradients as the analysis prematurely relaxes to the first guess/background field.

4. Evaluations of MODAS Versus RTG SST Over the Global Ocean

[24] While comparisons of SST images are useful at selected regions (section 3), they do not provide detailed information over the entire global ocean at various time periods. In this section, we will present such global evaluations for daily MODAS and RTG SSTs. In particular, we will identify where in the global ocean the products agree or disagree. MODAS SSTs are available since the first day of 1993, and RTG SSTs are available since Feb 2001. For consistency, we compare the two data sets over the years 2002–2005, a common time period for both products.

4.1. Statistical Metrics

[25] RTG SSTs are first interpolated to MODAS grid (1/8°), so that both products can be on the same grid over the global ocean. Yearlong time series of SST at each ocean grid point from MODAS and RTG are then compared using various statistical metrics: mean error (ME), root-mean-square (RMS) difference, correlation coefficient (R) and non-dimensional skill score (SS). To examine how and where both data sets differ on inter-annual time scales, we apply statistical analysis year by year starting from 2002 through 2005. This will also reveal, if present, systematic biases between the two products.

[26] Statistics are calculated based on daily time series. Let X_i ($i = 1, 2, \ldots, n$) be the set of n MODAS (reference) SST values, and let Y_i ($i = 1, 2, \ldots, n$) be the set of n RTG SST values. In addition, let $\overline{X}$ ($\overline{Y}$) and σ_X (σ_Y) be the means and standard deviations of the MODAS (RTG) values, respectively. Following *Murphy* [1995] and *Wilks* [1995], the statistical metrics used throughout the paper are expressed as follows:

$$\mathrm{ME} = \overline{Y} - \overline{X}, \tag{1}$$

$$\mathrm{RMS} = \left(\frac{1}{n} \sum_{i=1}^{n} (Y_i - X_i)^2 \right)^{1/2}, \tag{2}$$

$$R = \frac{1}{n} \sum_{i=1}^{n} (X_i - \overline{X})(Y_i - \overline{Y}) / \sigma_X \sigma_Y, \tag{3}$$

$$\mathrm{SS} = R^2 - \underbrace{[R - (\sigma_Y/\sigma_X)]^2}_{B_{\mathrm{cond}}} - \underbrace{[(\overline{Y} - \overline{X})/\sigma_X]^2}_{B_{\mathrm{uncond}}}, \tag{4}$$

where n is equal to 365 (366 for 2004) at each grid point over the global ocean for a given year.

[27] In particular, ME is the annual mean SST difference between MODAS and RTG values. RMS can be considered as an absolute measure of the distance between the SST time series from both products. The R value is a measure of the degree of linear association between the MODAS and RTG SSTs. As described by *Murphy* [1988], SS in equation (4) includes two non-dimensional biases (conditional bias, B_{cond}, and unconditional bias, B_{uncond}). Since these two biases are not taken into account in the correlation, SS serves as a relatively more valuable statistical metric. B_{uncond} (also called systematic bias) is a non-dimensional measure of the difference between the mean values of the MODAS and RTG time series. B_{cond} is a measure of the relative amplitude of the variability in the two. An examination of SS in equation (4) reveals that R^2 is equal to SS only when B_{cond} and B_{uncond} are zero. Because these two biases are never negative, the R value can be considered to be a measure of "potential" skill, i.e., the skill that one can obtain by eliminating all relative bias between MODAS and RTG SST. A SS value of 1.0 indicates that SSTs from MODAS and RTG are identical, i.e., they agree perfectly well. SS can be negative if there is no skill (poor agreement) between MODAS and RTG SSTs.

4.2. Statistical Comparisons of MODAS Versus RTG SST

[28] Comparisons of SST between MODAS and RTG are performed using the statistical metrics described in section 4.1. Figure 3 presents spatial fields of ME, RMS SST difference and non-dimensional SS values between daily SST time series from both products for 2002, 2003, 2004, 2005 and 2002–2005 as well. Note that regions where ice is present (e.g., high northern and southern latitudes) are masked and shown in gray. A mask is applied since MODAS does not have a specific treatment for SSTs over ice. The ice-free regions are determined from an ice land mask over the global ocean [*Reynolds et al.*, 2002]. The ice land mask is a function of the ice analysis and may change periodically. For this reason, a climatological mean for the mask is used.

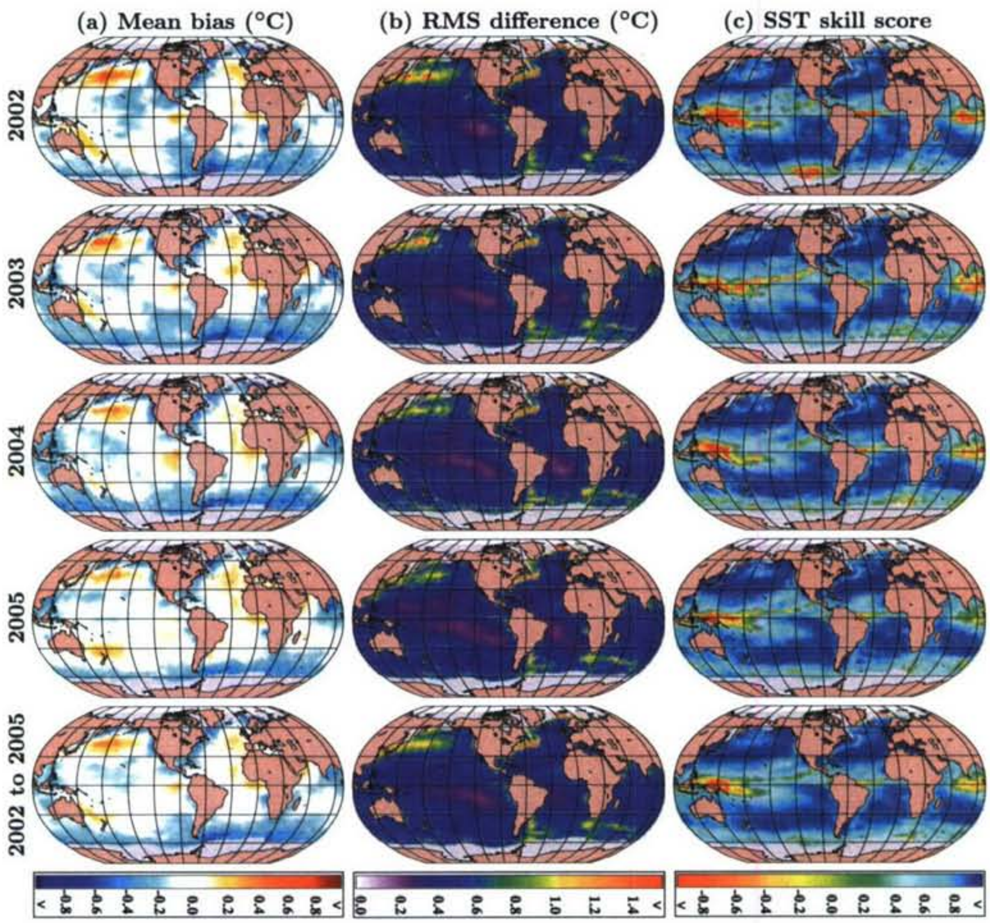

Figure 3. Spatial maps of annual mean error (ME), RMS SST difference and SST skill score (SS) between MODAS and RTG by year from 2002 through 2005. The number of cases is 365 (366 for 2004) at each grid point in the time series analysis. Mean statistics calculated for all years (2002–2005) is also shown in the last row. Statistical metrics are described in the text, in detail. Ice-covered regions are shown in gray and are not used in the statistical analysis.

[29] The bias (i.e., ME) fields are broadly similar to each other within the accuracy of $\pm 0.2°$ over the most of global ocean for all years (Figure 3a). The RTG SST is typically colder ($\approx 0.2°C$) than the MODAS SST at high southern latitudes, some parts of the northern Indian Ocean and a few other regions. However, the former is warmer than the latter in other, smaller parts of the global ocean. Locations of such warm and cold biases do not generally change depending on the year, including the 4-year mean period from 2002 to 2005. We will later examine whether or not these biases are systematic (i.e., the bias due to mean, B_{uncond}). Similar to the annual mean SST bias, the RMS SST difference between MODAS and RTG is small, typically ($<0.4°C$) over the most of global ocean in all years (Figure 3b). In fact, it is even ($<0.2°C$) over the large extent of tropical and subtropical Pacific and Atlantic Oceans. The largest RMS SST differences of $\approx 1°C$ are noted only in the northwestern Pacific, including the Kuroshio Current System, at high latitudes. The same is also true within region surrounding the Gulf Stream, where the relatively coarse RTG SST does not resolve the pathways accurately.

[30] Remarkable agreement between MODAS and RTG SST is evident from positive SS values over most of the global ocean (Figure 3c). Blue (red) colors in the maps are representative of good (poor) relationship between the two products. For most of the ocean, SS values are close to 1, indicating nearly perfect agreement. Yet, some areas of poor agreement between MODAS and RTG are plainly evident. For example, non-dimensional SS maps for all years clearly reveal that the agreement between the two is very poor (negative SS values) within three regions: (1) the warm pool in the western equatorial Pacific Ocean, (2) western portions of the equatorial Atlantic Ocean, and (3) the eastern part of the northern Indian Ocean. However, RMS SST differences are also very small within these regions, indicating close agreement in absolute temperature.

[31] Because SS normalizes RMS SST difference using standard deviation (see equation (4)), the SS results provide insight beyond RMS SST difference into the nature of SST differences between the two products. As expected, SST standard deviation is generally very small (e.g., $<0.5°C$) over the equatorial Pacific warm pool. Therefore, the corresponding RMS SST difference is expected to be small

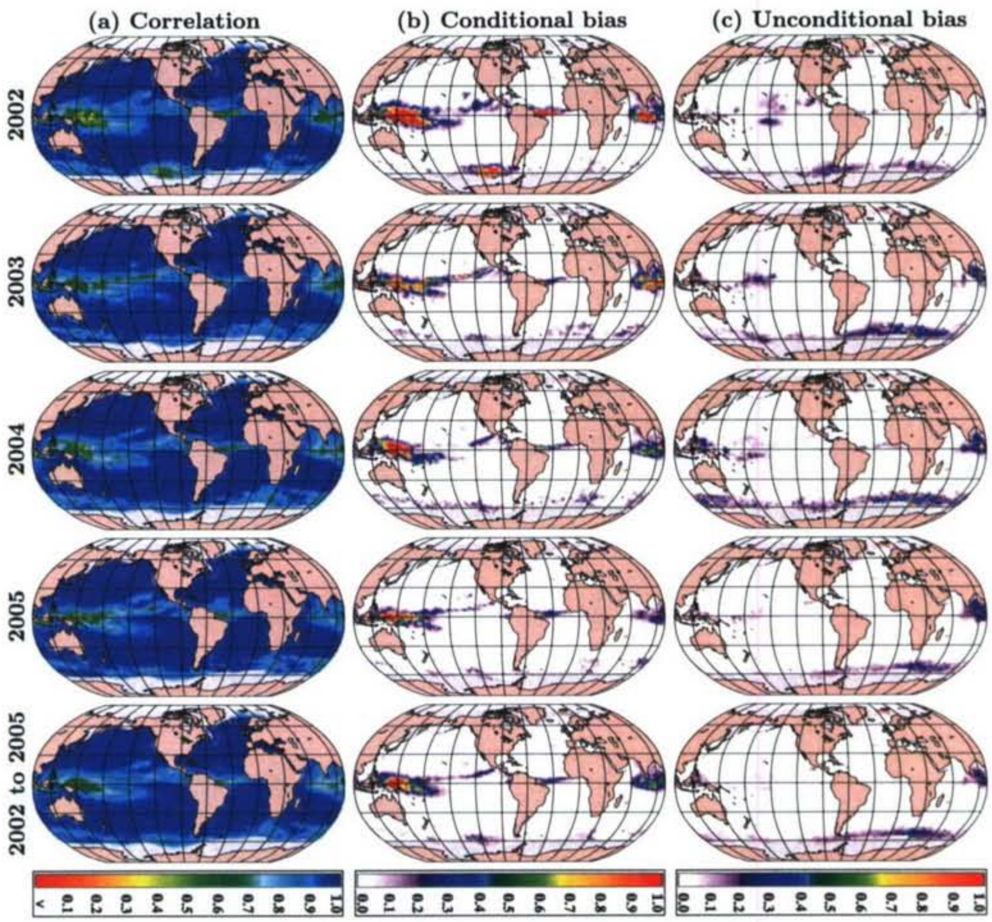

Figure 4. Same as Figure 3 but for correlation coefficient (R), conditional (B_{cond}) and unconditional (B_{uncond} biases between MODAS and RTG SST. Note that color palettes for B_{cond} and B_{uncond} have same scales.

as well and does not on its own necessarily imply good agreement between the two products. A random SST variation with the correct mean and small variance would produce small RMS SST differences even though it does not even attempt to follow local SST changes. Thus, using RMS difference alone may result in misleading information when assessing MODAS vs RTG SST performance at different locations of the global ocean.

[32] The non-dimensional SS includes R, B_{cond} and B_{uncond} biases (see equation (4)); each of these components is shown in Figure 4 by year. Previously, low skill between MODAS and RTG was noted in three regions: the western equatorial Pacific warm pool, the western equatorial Atlantic, and eastern parts of the northern Indian Ocean. These are regions where R (B_{cond}) is relatively low (high), explaining that most of the SST biases in these regions are due to differences in standard deviations (relatively large B_{cond}) between MODAS and RTG SST. B_{uncond} values are generally <0.1 over the global ocean for each year from 2002 through 2005, and all years as well. This implies no systematic bias between MODAS and RTG SSTs, i.e., both products have almost identical means except in the very high southern latitudes.

[33] There are also relatively large biases between MODAS and RTG in the high southern latitudes (Figure 3a), and SST skill is relatively low (Figure 3c), which is due mostly to the unconditional bias (Figure 4c). Since there are few in situ observations in this region, both MODAS and RTG must rely on AVHRR observations. Cloudy conditions will degrade the performance of both systems. In addition, seasonal changes in sea-ice extent will have a negative impact on the MODAS analysis. Finally, no satellite observations extend poleward of 70° in both northern and southern hemispheres, further reducing high-latitude SST accuracy. It is not clear whether MODAS or RTG is more reliable within this particular region. Parts of the northern Indian Ocean show relatively large B_{cond} and B_{uncond} as well, which may be tied to seasonally reversing monsoon winds that affect the cloudiness and precipitation patterns and thereby SST analyses.

[34] Zonal averaging for each statistical metric presented in Figures 3 and 4 are computed to better reveal differences between MODAS and RTG SSTs. Zonal averages of ME, RMS, SS, R, B_{cond} and B_{uncond} are shown in Figure 5 for all time periods (2002–2005). Bias between the two (RTG-MODAS) are within ±0.2°C except at latitudes of south of 40°S. There are R values >0.9 and positive SS values in

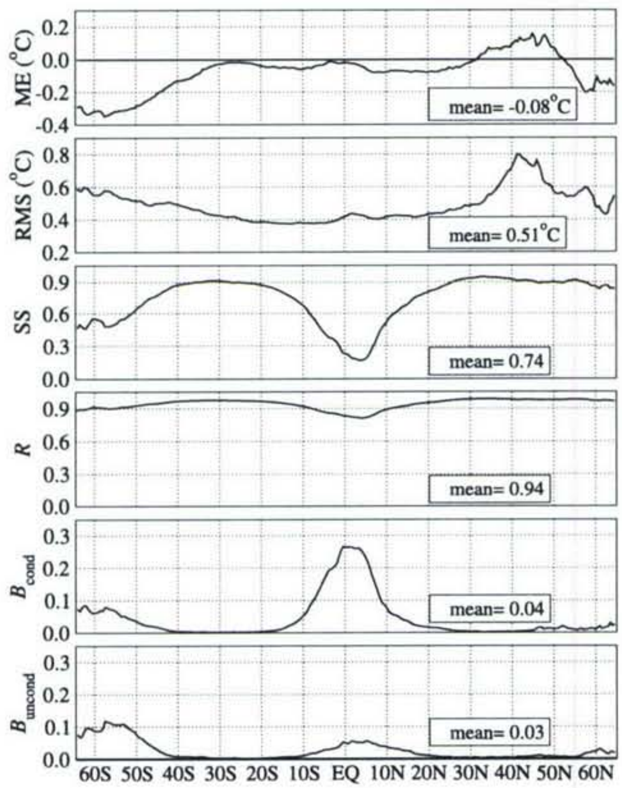

Figure 5. Zonal averages of statistical metrics calculated during 2002–2005 shown in bottom panels of Figures 3 and 4. Zonal averaging is performed at each 0.5° latitude belt at the ice-free regions over the global ocean. Note that mean error is RTG-MODAS.

nearly all latitude belts. The largest (smallest) B_{cond} (SS) values are noted along the equatorial region. This explains that the relatively poor agreement in SST in these regions are due to standard deviations being relatively different between MODAS and RTG, since biases due to mean (i.e., B_{uncond}) are negligible for almost all latitude belts, including the equatorial regions.

5. SST Time Series Comparisons Among MODAS, RTG and Buoys

[35] One main difference between MODAS and RTG is that while the former only uses satellite measurements to construct SST, the latter makes use of both satellite and in situ data. One question arises, "can MODAS produce accurate SSTs without using any in situ data?" This will be discussed in this section.

[36] MODAS SST is based solely on the NLSST (see section 3.1) produced by NAVOCEANO from the global AVHRR observations. In situ observations only enter the processing during the initial determination of the NLSST regression coefficients, when the NLSST returns are calibrated with SST measurements from drifting buoys and mooring arrays (see section 5.1). NODC buoys have not entered into the data stream for the NLSST calibrations. Thus, buoy SST measurements are independent of the MODAS SST except for a collective link during sensor calibration. In contrast, RTG SST directly includes buoy measurements in its daily analysis procedure.

5.1. Evaluation Against Individual Buoy SSTs

[37] Buoy times series are particularly useful for examining the temporal fidelity and variability of the SST data. For accuracies of daily MODAS and RTG products we have used observational buoy SST time series, existing in various regions over the global ocean (Figure 6). Daily SST time series are obtained from three sources: (1) the Tropical Atmosphere-Ocean (TAO) array [*McPhaden et al.*, 1998], (2) the Pilot Research Moored Array (PIRATA) [*Servain et al.*, 1998], and (3) the National Oceanic Data Center

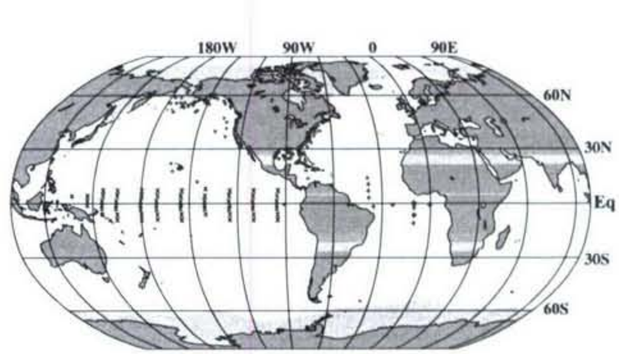

Figure 6. Mooring buoy locations where daily SST time series from MODAS and RTG are compared from 2002 through 2005: TAO buoys are marked with asteriks, PIRATA buoys with pluses and NDBC buoys with squares.

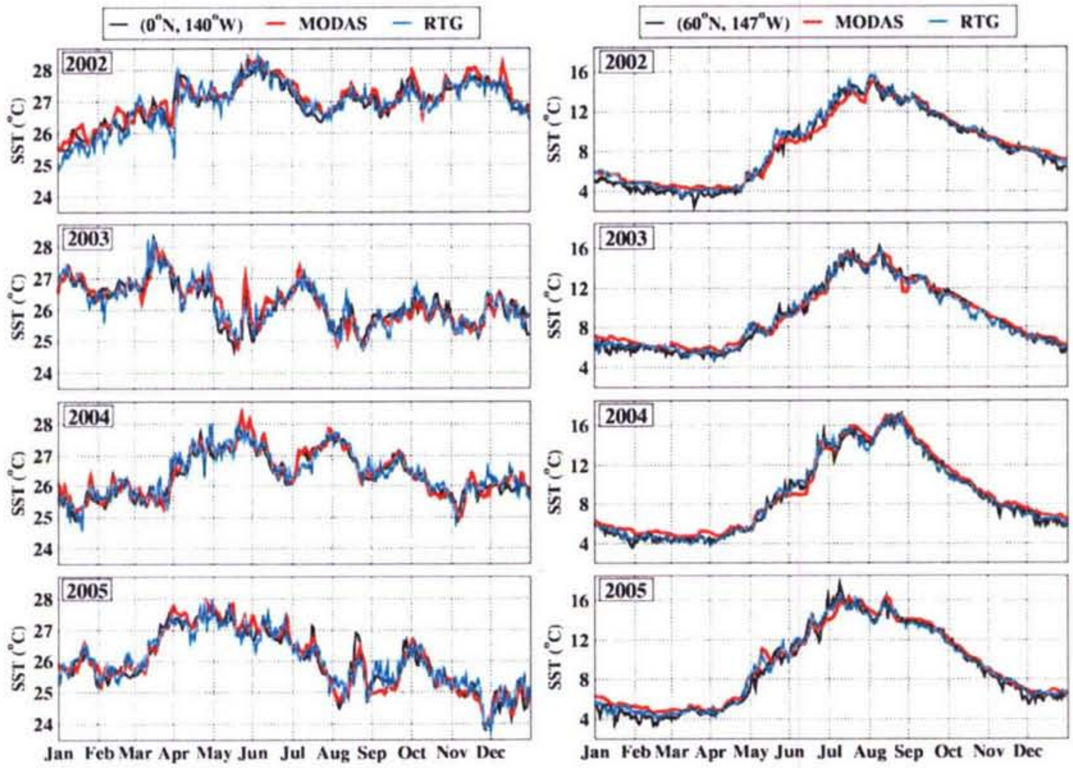

Figure 7. Daily SST time series from a TAO buoy at (0°N, 140°W) and NDBC buoy at (60°N, 147°W) (black) and those from MODAS (red) and RTG (cyan) as well in each year during 2002–2005. Any missing buoy SSTs are filled using linear interpolation. In all plots, the x–axis is labeled starting from the beginning of each month.

(NODC) database (http://www.nodc.noaa.gov/BUOY/buoy.html).

[38] The TAO array, located in the equatorial Pacific Ocean, consists of approximately 70 buoys between 8°S–8°N and 137°E–95°W. The PIRATA is an array of 12 buoys in the Tropical Atlantic, and they are very sparse in comparison to the TAO buoys. The NODC database holds different types of buoy observations collected by the National Data Buoy Center (NDBC), and these buoys are located at various region, including the Gulf of Mexico, Northwest/Southwest U.S. coast, Great Lakes, Hawaii and Alaskan coasts. Buoys from the Great Lakes are not used since MODAS SST analysis does not include that region.

[39] TAO, NDBC and PIRATA buoys report hourly SST measured at a depth of 1 m below the sea surface. For comparisons of MODAS and RTG we constructed daily averaged SSTs from all buoys. No smoothing was applied to the original buoy SSTs. Time series with more than a few small gaps (>1 month) are excluded. For the remaining buoys, data gaps in SSTs, if any, are filled by linear interpolation for a given year.

[40] One challenge was how best to compare intermittent time series of different lengths and covering different time intervals, while allowing inter-annual comparison of verification statistics at the same location and comparison of statistics at different locations over the same time interval. As a result, the time series were divided into 1 year segments with daily averaged SSTs. This approach also facilitates later inter-product comparisons. Sufficiently detailed results are included here for MODAS and RTG to be an initial benchmark for such comparisons.

[41] One note about the model validation procedure is that positions of moored buoys can change by up to ≈3 km over the course of a few days to a week, depending on the local current regime. This is the diameter within which the buoy moves. Since each mooring moves in time and space from its deployment position, we calculated average position based on the historical latitude and longitude data for each buoy. Thus, MODAS and RTG SSTs were extracted using the average latitude and longitude values at a given buoy location. For ease of notation, hereinafter, nearest integer values of average latitude and longitude are used for each buoy throughout the text.

[42] As examples to illustrate the SST assessment procedure between MODAS and RTG in the paper, detailed comparison results are presented at two different buoy locations where SST variation over the course of a given year can be quite different (Figure 7). One of these buoys, a TAO buoy (0°N, 140°W), is located in the eastern central Pacific Ocean, and the other one, a NDBC buoy (60°N, 147°W) (NDBC station ID is 46061) is located off the Alaska coast. Yearlong SST time series comparisons are compared in 2002, 2003, 2004 and 2005.

[43] Overall, SSTs from MODAS and RTG agree with those from two buoys quite well. Consistent with the buoy, both products reproduce inter-annual variations of SST. The

Table 1. Statistical Verification of Daily SST at (0°N, 140°W) and (60°N, 147°W)[a]

Year	(0°N, 140°W)	RMS, °C	ME, °C	σ_X, °C	σ_Y °C	R	SS
2002	Buoy vs MODAS	0.25	0.10	0.61	0.62	0.93	0.83
	Buoy vs RTG	0.30	−0.06	0.61	0.71	0.91	0.77
	MODAS vs RTG	0.33	−0.17	0.62	0.71	0.92	0.72
2003	Buoy vs MODAS	0.26	0.03	0.65	0.67	0.93	0.84
	Buoy vs RTG	0.30	0.02	0.65	0.66	0.90	0.79
	MODAS vs RTG	0.29	−0.01	0.67	0.66	0.91	0.81
2004	Buoy vs MODAS	0.21	0.06	0.69	0.73	0.96	0.91
	Buoy vs RTG	0.27	0.05	0.69	0.71	0.93	0.84
	MODAS vs RTG	0.26	−0.01	0.73	0.71	0.93	0.87
2005	Buoy vs MODAS	0.23	0.02	0.92	0.96	0.97	0.93
	Buoy vs RTG	0.32	0.03	0.92	0.86	0.94	0.88
	MODAS vs RTG	0.30	0.01	0.96	0.86	0.95	0.90
Year	(60°N, 147°W)	RMS, °C	ME, °C	σ_X, °C	σ_Y °C	R	SS
2002	Buoy vs MODAS	0.63	0.25	3.65	3.36	0.99	0.97
	Buoy vs RTG	0.49	0.30	3.65	3.56	0.99	0.98
	MODAS vs RTG	0.53	0.05	3.36	3.56	0.99	0.97
2003	Buoy vs MODAS	0.58	0.23	3.27	3.07	0.99	0.97
	Buoy vs RTG	0.48	0.00	3.27	3.17	0.99	0.98
	MODAS vs RTG	0.53	−0.23	3.07	3.17	0.99	0.97
2004	Buoy vs MODAS	0.41	0.03	4.05	4.01	0.99	0.99
	Buoy vs RTG	0.41	0.03	4.05	4.01	0.99	0.99
	MODAS vs RTG	0.60	−0.30	3.94	4.01	0.99	0.98
2005	Buoy vs MODAS	0.73	0.38	4.10	3.80	0.99	0.97
	Buoy vs RTG	0.56	0.16	4.10	3.90	0.99	0.98
	MODAS vs RTG	0.51	−0.22	3.80	3.90	0.99	0.98

[a]The former (TAO) buoy is in the central equatorial Pacific Ocean, and the latter (NDBC) buoy is at the Alaskan Coast. Statistical calculations are based on 365 (366 in 2004) daily SST time series. In the table, regarding standard deviations, for example, for buoy vs MODAS, σ_X denotes the SST standard deviation for the former (i.e., buoy) and σ_Y denotes the SST standard deviation for the the latter (i.e., MODAS). Similarly, in the case of MODAS vs RTG, σ_X denotes the SST standard deviation for MODAS and σ_Y denotes the one for RTG. See text for details of calculations for each statistical metric.

remarkable accuracy of MODAS and RTG in comparison to the buoy is also evident from statistical comparisons between the pairs of buoy vs MODAS and buoy vs RTG (Table 1). Also included are statistical comparisons for MODAS vs RTG, whose spatial statistical maps are already presented in Figures 3 and 4. The same statistical metrics, presented in section 4.1, are applied for comparisons between buoy and MODAS (or RTG) SSTs. In equations (1) through (4), the reference data set (i.e., X) represents SST time series from buoy, and the corresponding estimates (i.e., Y) are those from MODAS or RTG. Based on daily SST time series analysis, annual mean SST biases are generally negligible with values very close to zero. Both MODAS and RTG are able to capture the phases of SST variability successfully, as noted by large correlation values close to 1. The success of both products in representing daily SST is also confirmed by large SS values (close to perfect, i.e., 1).

[44] As demonstrated in Figure 3c in section 4, there are generally three regions where there is poor SST skill between MODAS and RTG. However, that analysis does not reveal which product is more accurate in these regions. One of these regions is the western equatorial Pacific warm pool. The availability of TAO buoys in the warm pool allows us to investigate accuracy of both products. For example, SST time series from MODAS, RTG and buoy are analyzed at (0°N, 165°E) in 2002 (Figure 8). In comparison to the buoy, the SST from MODAS clearly has more biases than that from RTG.

[45] The western equatorial Pacific warm pool is well-known to have high cloudiness due to convective systems [e.g., *Chen and Houze*, 1997; *Godfrey et al.*, 1998; *Houze et al.*, 2000]. In fact, a necessary condition for the development and persistence of deep convection (e.g., enhanced cloudiness and precipitation) is to have SSTs >28°C [e.g., *Holton*, 1992], a common feature of the warm pool. Because MODAS only uses infrared satellite SSTs, there might be long periods of time when input data for the analysis are sparse or not available due to persistent cloud cover. To identify periods of extensive cloud cover, we calculated the number of NLSST measurements each day within a 2° latitude by 2° longitude window centered at (0°N, 165°E). The median daily number of observations was 32 over the period 2002–2005. Table 2 further gives annual median number of observations by year. Of these years, 2002

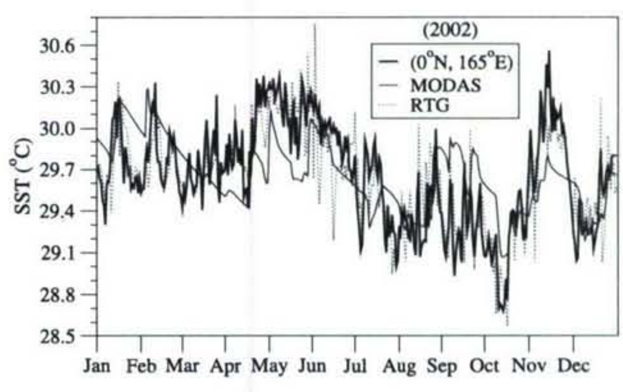

Figure 8. Daily SST time series from a TAO buoy at (0°N, 165°E) located in the western equatorial Pacific warm pool (dark black line) in 2002. Also given are SST time series from MODAS (thin black line) and RTG (dotted line). The x-axis is labeled starting from the beginning of each month.

Table 2. Statistics of the Number of Daily NAVOCEANO Nonlinear SST Data[a]

Year	Days	Mean	Median	S. Dev.
2002	365	73	4	145
2003	365	237	73	359
2004	366	210	51	362
2005	365	125	40	193

[a]All values are based on annual analysis from 2002 through 2005, covering the region within a 2° (latitude × longitude) box centered at (0°N, 165°E). Standard deviation (S. Dev.) of daily values is also given.

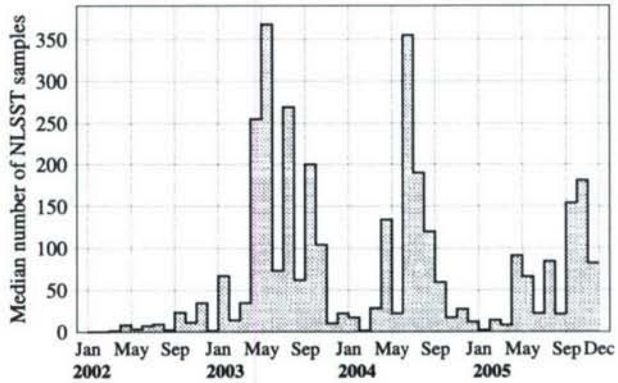

Figure 9. Median number of daily nonlinear SST observations entering the MODAS SST analysis by month, covering the region within a 2° latitude × longitude box centered at (0°N, 165°E) during 2002–2005.

was the cloudiest time period, with the median of 4 observations per day.

[46] The monthly distribution of median daily number of observations is below 10 for each month from January to September 2002 and almost no observation from January to March 2002 (Figure 9). The sparse data over this period resulted in less reliable SSTs from the MODAS analysis at (0°N, 165°E) during 2002. Since buoy SSTs are used in the RTG analysis, RTG near buoy locations should be less affected by missing AVHRR data. Figure 8 and Table 3 indicate close agreement between the buoy and RTG SST time series, as expected.

[47] Comparisons at this location during another year, 2004, reflect the improved performance of MODAS SST under less cloudy conditions that allow more frequent NLSST measurements. The median daily number of NLSST observations was 51, the second largest annual number from 2000–2005 and smaller than the multi-annual median, but an order of magnitude larger than the 2002 median. Figure 10 shows much better agreement between the MODAS and buoy SSTs, further confirming the accuracy of MODAS SST analysis when more satellite measurements are available. Based on Table 2, the performance of MODAS should have also improved in 2005 compared to 2002 since there are more satellite measurements available in the former year. However, SST skill does not really indicate such improvement in 2005 (Table 3). This is a consequence of small RMS and small SST standard deviation. Even though the RMS SST difference between MODAS and the buoy measurements is smaller in 2005, the smaller variability in the buoy SST reduces skill in 2005. In any case, there are not remarkable differences in the statistical results in 2002 and 2005.

[48] We also note that large spikes exist in the RTG SSTs (Figures 8 and 10). This is most likely a consequence of the irregular availability of AVHRR data. For example, on some days AVHRR and buoy data are combined together, while on other days only buoy measurements are available. Inconsistences in instrument calibration, associated with day/night SSTs [e.g., *Gentemann et al.*, 2003], may also contribute to differences between buoy and AVHRR SSTs.

[49] As mentioned in section 2, buoy data is regularly incorporated in the RTG analysis and is used the the initial calibration of NLSST that is used by MODAS. We use SSTs from two buoys that were included neither in MODAS nor in RTG analyses to perform a purely independent comparison. These time series of hourly SST are obtained the U. K. Meteorological Office in 2002 (M. Bolt, personal communication). Daily averages of SST are then constructed at two locations and compared to SST products (Figure 11). One buoy (47.5°N, 8.50°W) is owned and maintained by U. K. Meteorological Office in cooperation with Meteo France, whose real-time measurements are also available from NDBC web site (station ID is 62163). The NDBC station ID for the other U. K. buoy (59.1°N, 11.4°W) is 64045. As

Table 3. Same as Table 1 but at (0°N, 165°E)[a]

Year	(0°N, 165°E)	RMS, °C	ME, °C	σ_X, °C	σ_Y, °C	R	SS
2002	Buoy vs MODAS	0.33	0.00	0.38	0.25	0.49	0.25
	Buoy vs RTG	0.22	−0.01	0.38	0.36	0.83	0.67
	MODAS vs RTG	0.32	−0.01	0.25	0.36	0.48	−0.64
2004	Buoy vs MODAS	0.26	0.06	0.38	0.33	0.74	0.53
	Buoy vs RTG	0.25	0.00	0.38	0.38	0.79	0.57
	MODAS vs RTG	0.30	−0.06	0.33	0.38	0.68	0.18
2005	Buoy vs MODAS	0.25	0.01	0.27	0.25	0.54	0.14
	Buoy vs RTG	0.24	−0.07	0.27	0.31	0.69	0.21
	MODAS vs RTG	0.31	−0.08	0.25	0.31	0.44	−0.54

[a]The TAO buoy is located in the western equatorial Pacific warm pool. Note that for very small RMS values, SS values shown on the table are not very precise. This is because we only provide two decimal digits for SS while very small RMS and σ_X values, which are used for actual calculations, can change the skill. Note also that the statistical results are not shown for 2003 since buoy SSTs are missing on many days. Meanings of σ_X and σ_Y for each pair are given in Table 1.

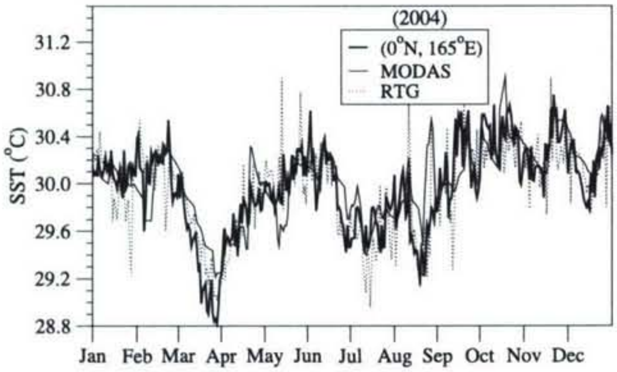

Figure 10. The same as Figure 8 but in 2004.

before, nearest integer values of average latitude and longitude are used for each buoy in Figure 11. Mean SST bias for MODAS and RTG with respect to buoy is within 0.1°C at both locations during 2002. Note that unlike other buoys used in the paper, the buoy SST is measured at a depth of ≈1.5 m (rather than 1 m) below the sea surface. Thus, some of the SST errors in comparison to buoy can be attributed to the measurement depth. Overall, both products can reproduce SST variability and seasonal cycle quite well.

5.2. Combined Statistics Using All Buoy SSTs

[50] Our major goal in this section is to assess overall performance of MODAS and RTG in representing SST over the time period 2002–2005. The SST time series comparisons among MODAS, RTG and buoy, like those performed at (0°N, 140°W) and (60°N, 147°W) as seen from Figure 7, are applied to all TAO, NDBC and PIRATA buoys. The buoys yield 97, 109, 109 and 105 yearlong daily SST time series analysis in 2002, 2003, 2004 and 2005, respectively, for a total of 420 yearlong time series. Here we represent each yearlong time series as one count per buoy, giving us the equivalent 420 buoys. In the text and figures, we will refer to these as 420 buoys (rather than 420 yearlong time series).

[51] For each time series, statistical metrics are calculated in a similar way as presented for the two buoys in Table 1. This simply means that based on a yearlong daily SST time series we calculate ME, RMS, *R* and SS between the pairs of buoy vs MODAS, buoy vs RTG and MODAS vs RTG at each buoy location (Figure 6). If a buoy has data voids longer than one month in a given year, it is excluded from the evaluation analysis. Missing SSTs <1 month are filled using a linear interpolation to be used for the evaluations. ME, RMS, *R* and SS are analyzed separately, each yielding 420 values.

[52] Figure 12 shows histograms for each statistical metric. Most of ME values between the pairs of products are between −0.2°C and 0.2°C, and RMS SST differences are typically <0.4°C. The agreement between MODAS and RTG (i.e., MODAS vs RTG) is at least as good as the one between the pairs of buoy vs MODAS and buoy vs RTG as evident from non-dimensional SS values. Similarly, SST standard deviation from MODAS and RTG based on 420 buoys during 2002–2005 also agrees with that from buoys well (Figure 13).

[53] Cumulative frequency is another way of expressing the number of ME, RMS, *R* and SS values that lie above (or below) a particular value (Figure 14). The cumulative frequency is calculated as the percentage of the values within each interval, providing an easier way to determine the effectiveness of MODAS and RTG in producing daily SST in comparison to buoy SSTs during 2002–2005. For example, ≈75% of the RMS SST differences are <0.6°C, ≈ 80% of the *R* values are >0.8, and only a few percentages of SS values are <0.0. This is generally true for pairs of buoy vs MODAS, buoy vs RTG and MODAS vs RTG based on 420 buoys.

[54] Median values (corresponding to 50%) for ME, RMS, *R* and SS are very close to each other for each pair (Table 4). The remarkable agreement among all products are evident from median RMS SST difference value of ≈0.4°C, and median SS value of ≈0.85. Median SST bias is almost zero. SST standard deviation from all products are almost identical as well (Figure 15). Median error statistics based on individual years also confirms consistency of results on the inter-annual time scales. For example, median SS values of 0.85 do not change significantly by year even though we have different numbers of buoys where the median values are calculated for each year (Table 4).

6. Conclusions

[55] The usefulness of any particular ocean product is generally tested by examining its accuracy for a variety of

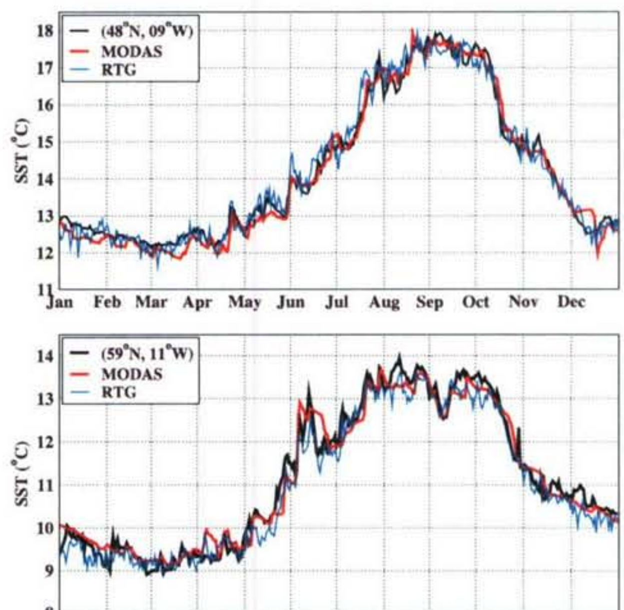

Figure 11. Daily SST time series from two buoys maintained by the U.K. Meteorological Office, at (48°N, 09°W) and (59°N, 11°W) in 2002. Also included are those from MODAS and RTG analyses. The x-axis is labeled starting from the beginning of each month.

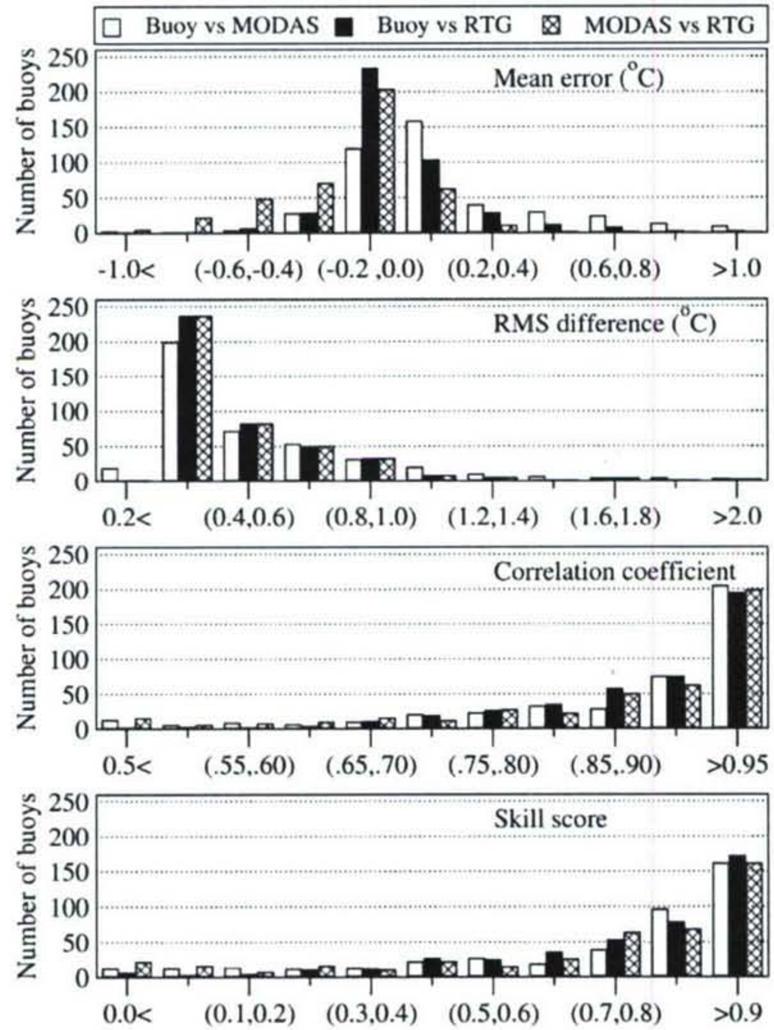

Figure 12. The total number of buoys given for class intervals of each statistical metric (ME, RMS, R and SS) based on daily SST comparisons. In the analysis, daily SST time series from all buoys are used from 2002 through 2005. A buoy can have multiple yearlong daily SST time series, and here represent each yearlong time series as one count of buoy. This means there are a total of 420 yearlong daily SST time series from TAO, NDBC and PIRATA buoys. A class interval of (0.2, 0.4) in the mean error, for example, indicates values >0.2 but ≤0.4.

conditions on both short (e.g., daily) and longer (e.g., annual) time scales. Thus, any product that is developed toward operational or real-time use needs to go through a rigorous evaluation. The evaluation assists potential users in determining whether or not the accuracy and representativeness of the results obtained from that product are reasonable for a particular application. In this paper, we present such a validation for two operational systems (MODAS and RTG), which provide gridded daily SST over the global ocean.

[56] We first perform a comprehensive statistical evaluation for daily SSTs between MODAS and RTG at each grid point over the global ocean year by year (2002, 2003, 2004 and 2005) and for all years together (2002–2005). Global average of bias (RTG-MODAS) is −0.08°C, RMS SST difference is 0.51°C, skill score is 0.74, and correlation coefficient is 0.94. There are almost no conditional or

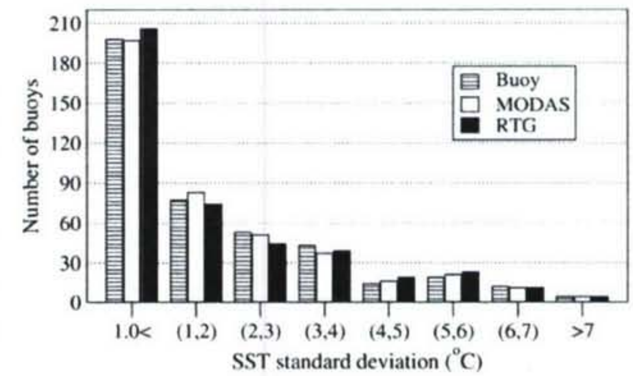

Figure 13. Class interval for SST standard deviations from buoy, MODAS and RTG. Results are based on 420 yearlong daily SST time series during 2002–2005. SST standard deviation is calculated at each buoy separately for each year.

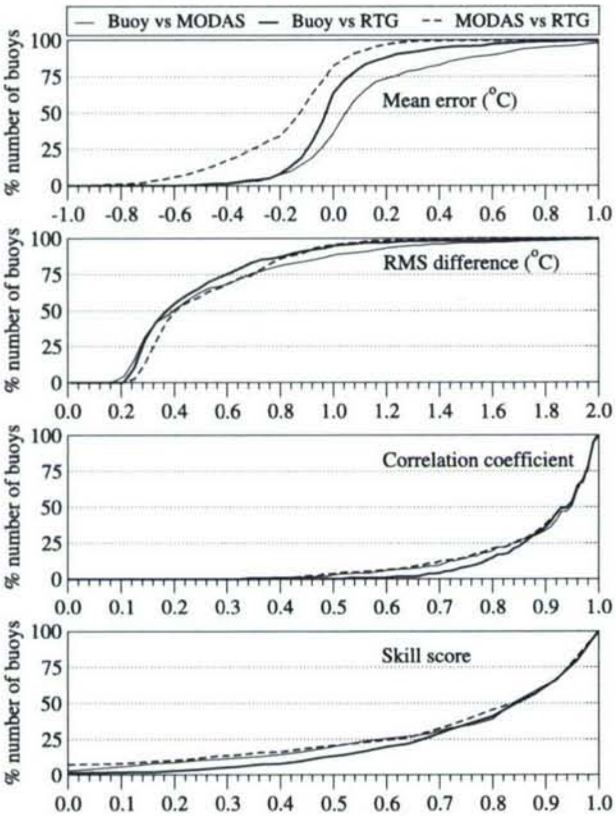

Figure 14. The percentage cumulative frequencies of statistical metrics shown in Figure 12. Median value corresponds to 50% in each panel.

unconditional biases (near zero) between both products, indicating that biases due to standard deviation and mean are generally negligible. However, that is not true around the tropical ocean (e.g., from 5°S to 5°N), mainly in the western equatorial Pacific warm pool, where both biases, particularly the bias due to standard deviation, are relatively high and lead to low skills. Additional analyses indicate that these are the regions where RTG SSTs are more reliable than MODAS due to the inclusion of in situ (e.g., the validation buoy) SSTs in the RTG analysis procedure.

[57] We then use an extensive set of daily SSTs from NODC, TAO and PIRATA buoys located in various regions (e.g., Northwest/Southwest U. S. coast, Hawaii and Alaskan coasts, equatorial Pacific and Atlantic Oceans) over the global ocean from 2002 through 2005. Error statistics with respect to all 420 buoys (i.e., 420 yearlong) daily SST time series over the time frame 2002–2005 gave median mean bias for MODAS (RTG) of 0.05°C (−0.02°C), RMS SST difference of 0.38°C (0.36°C), correlation of 0.94 (0.94) and skill score of 0.84 (0.85). Overall, MODAS and RTG SST agree with each other very well, with median mean bias (RTG-MODAS) value of −0.12°C, RMS SST difference of 0.40°C, correlation of 0.94 and skill score of 0.84.

[58] While the magnitude of SST from MODAS and RTG are reliable and very close to each other, there are some notable difference in spatial variations (e.g., SST patters, fronts, etc.). For example, an examination of very fine resolution satellite images reveals that RTG SSTs can be limited in representing small scale feature within strong current systems, such as the Gulf Stream. These details are better represented in the MODAS SST analysis due to its higher resolution and shorter error covariance scales. The 1/2° resolution of RTG is not adequate to resolve such current systems. A higher resolution (1/12°) RTG SST product became available in 2005.

[59] A 1/12° SST fields developed in the Multi-sensor Improved Sea Surface Temperature (MISST) for GODAE project is being similarly evaluated at NRL as an upgraded NAVOCEANO product. The new SSTs incorporates infrared, microwave and in situ SST observations. We hope such a product will resolve some of the limitations of coarse spatial resolution while making better use of the available SST data sources. Further studies are also underway. In particular, we have been examining the impact of additional satellite SST observation types, including microwave SST observations, which have coarser horizontal resolution but

Table 4. Median Error Statistics for Yearlong Daily Time Series by Year During 2002–2005[a]

Year	Evaluation	Buoy Count	RMS, °C	ME, °C	σ_X, °C	σ_Y °C	R	SS
2002	Buoy vs MODAS	97	0.44	0.10	1.14	1.24	0.93	0.84
	Buoy vs RTG	97	0.37	0.02	1.14	1.16	0.94	0.87
	MODAS vs RTG	97	0.41	−0.13	1.24	1.16	0.93	0.80
2003	Buoy vs MODAS	109	0.40	0.09	1.21	1.21	0.93	0.82
	Buoy vs RTG	109	0.37	−0.02	1.21	1.18	0.93	0.84
	MODAS vs RTG	109	0.43	−0.15	1.21	1.18	0.92	0.82
2004	Buoy vs MODAS	109	0.36	0.03	1.20	1.22	0.95	0.87
	Buoy vs RTG	109	0.37	−0.02	1.20	1.15	0.94	0.84
	MODAS vs RTG	109	0.38	−0.12	1.22	1.15	0.94	0.85
2005	Buoy vs MODAS	105	0.32	0.03	1.00	1.03	0.95	0.85
	Buoy vs RTG	105	0.34	−0.03	1.00	0.94	0.94	0.85
	MODAS vs RTG	105	0.37	−0.10	1.03	0.94	0.93	0.85
All	Buoy vs MODAS	420	0.38	0.05	1.12	1.10	0.94	0.84
	Buoy vs RTG	420	0.36	−0.02	1.12	1.07	0.94	0.85
	MODAS vs RTG	420	0.40	−0.12	1.10	1.07	0.94	0.84

[a]Also included is the median error statistics for all years (i.e., from 2002 to 2005). Results are given when using all TAO, NDBC and PIRATA buoys because a possible breakdown by the buoy source does not provide enough samples for calculating the median statistics.. The number of buoys (i.e., total yearlong SST time series) used in the statistical calculations is given in the third column. Meanings of σ_X and σ_Y for each pair are given in Table 1.

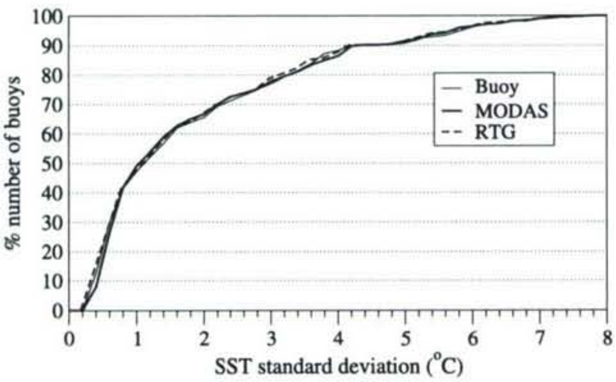

Figure 15. The percentage cumulative frequencies of SST standard deviation (see Figure 13).

are unaffected by cloud cover, and infrared SST observations from geostationary satellites, which provide high temporal resolution for portions of the globe.

Notation

AMSR	Advanced Microwave Scanning Radiometer.
AVHRR	Advanced Very-High Resolution Radiometer.
ECMWF	European Centre for Medium-Range Weather Forecasts.
ENSO	El Niño Southern Oscillation.
FNMOC	Fleet Numerical Meteorology and Oceanography Center.
GODAE	Global Ocean Data Assimilation Experiment.
LAS	Live Access Server.
MISST	Multi-sensor Improved Sea Surface Temperature.
MODAS	Modular Ocean Data Analysis System.
MODIS	Moderate Resolution Imaging Spectroradiometer.
NASA	National Atmospheric Space Administration.
NAVOCEANO	Naval Oceanographic Office.
NCEP	National Centers for Environmental Prediction.
NLSST	AVHRR nonlinear SST.
NOGAPS	Navy Operational Global Atmospheric Prediction System.
NRL	Naval Research Laboratory.
NWP	Numerical Weather Prediction.
ONR	Office of Naval Research.
PIRATA	Pilot Research Moored Array in the Tropical Atlantic.
RTG	Real-Time, Global.
TAO	Tropical Atmosphere-Ocean.

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